(54) Title: SCHEDULING METHODS FOR WIRELESS NETWORKS

(57) Abstract: The invention concerns routing, scheduling, and power control methods for single and multi-hop wireless networks.
A multi-hop network is one in which source and destination nodes may communicate directly or through relay nodes. Nodes in single
hop networks communicate without use of relay nodes. Embodiments of the invention may produce an optimal schedule to provide
for the best-case goal for a given parameter. In a preferred embodiment, total power is the parameter and total power is minimized
for the network. In another preferred embodiment, data throughput is the parameter, and throughput is maximized for the network.

SCHEDULING METHODS FOR WIRELESS NETWORKS

TECHNICAL FIELD

The field of the invention is wireless communications. The invention is particularly concerned with wireless networks, including single hop and multi-hop networks.

BACKGROUND ART

5   Using wireless radio frequency transmissions provides great freedom to configure networks. Wireless models become more popular because inconvenience and expenses associated with physical connectivity, i.e., through wires, are eliminated. The wireless model is also generally more flexible in that

10   the potential paths for communications are not constrained by any wired connection.

Limitations in the wireless communication model for networks include signal interference and power limitations, which both constrain data capacity. Signal interference is the natural interference inherent in wireless

15   communications. Power limitations arise from communication standards, e.g., the Federal Communication Commission standards in the United States, that limit the power that transmitters may use for a transmission. Power limitations also arise from the portable power sources sometimes used by nodes in wireless networks.

20   Power and data rate constraints have been addressed on a node to node level, but an efficient and systematic method for accounting for these constraints on a network wide basis is believed lacking. Yet, even modest efforts at

centralized scheduling in networks have made significant contributions to

increase network capacity. In the conventional IEEE 802.11 standard there is a

point coordinate function to centralize scheduling of users in a network. The

HDR (1EX VDO) standard also schedules transmissions centrally on downlink

5   channels. There remains a need, however, for a systematic approach that is

effective and computationally feasible.

DISCLOSURE OF THE INVENTION

10   The invention concerns routing, scheduling, and power control methods

for single and multi-hop wireless networks. A multi-hop network is one in which

source and destination nodes may communicate directly or through relay nodes.

Nodes in single hop networks communicate without use of relay nodes.

Embodiments of the invention may produce an optimal schedule to provide for

15   the best-case goal for a given parameter. In a preferred embodiment, total power

is the parameter and total power is minimized for the network. In another

preferred embodiment, data throughput is the parameter, and throughput is

maximized for the network.

BRIEF DESCRIPTION OF THE DRAWINGS

20

FIG. 1. is an exemplary network topology for application of methods of

the invention and used in a numerical simulation of an embodiment of the

invention;

FIG. 2 is a graph of total average transmit power versus network

25   throughput for three cluster schedules X, Y and Z reached in a numerical

simulation and applied to the network topology of FIG. 1;

FIG. 3 is a graph of total average transmit power versus network

throughput for the cluster schedules X, Y and Z reached in a numerical

simulation and applied to the network topology of FIG. 1;

FIG. 4 is an example transport style network for application of methods of the invention and used in a numerical simulation of an embodiment of the invention;

FIG. 5 plots the ratio of throughputs achieved by scheduling in accordance
5   with the invention compared to TDMA with increasing values of ambient noise for the network topology of FIG. 4;

FIG. 6 plots the total average power with increasing traffic rates for the session between node 1 and node 5 in the network topology of FIG. 4;

FIG. 7 illustrates an example asymmetric diamond topology for
10 application of methods of the invention and used in a numerical simulation of an embodiment of the invention;

FIG. 8 plots throughput ratios for simulations on the FIG. 7 network topology;

FIG. 9 plots average power required to achieve higher traffic demands for
15 the example FIG. 7 network topology;

FIG. 10 illustrates an example hierarchical network topology for application of methods of the invention and used in a numerical simulation of an embodiment of the invention; and

FIG. 11 plots the ratio of the total maximum throughput for a routing
20 policy produced by application of methods of the invention versus that using only minimum energy paths as a function of ambient noise and in the example topology of FIG. 10.

25   BEST MODE OF CARRYING OUT THE INVENTION

The invention concerns routing, scheduling, and power control methods for single and multi-hop wireless networks. A multi-hop network is one in which source and destination nodes may communicate directly or through relay nodes. Nodes in single hop networks communicate without use of relay nodes.
30 Embodiments of the invention may produce an optimal schedule to provide for

the best-case goal for a given parameter. In a preferred embodiment, total power is the parameter and total power is minimized for the network. In another preferred embodiment, data throughput is the parameter, and throughput is maximized for the network.

5   Embodiments of the invention also provide an integrated routing, link scheduling and power allocation policy for a general multi-hop network that minimizes the total average power consumption to support minimum average rate requirements per link. Multi-hop networks implementing methods of the invention can support higher throughputs than with conventional approaches to

10   radio resource allocation. Methods of the invention may be implemented in multi-hop networks that are time synchronized between transmitters, and are characterized by channel conditions that remain essentially constant over several time slots.

Methods of the invention are generally applicable to single and multi-hop

15   networks, but will not perform as efficiently in networks with rapidly changing channel conditions. The invention is particularly well-suited for application to networks of wireless nodes in a small geographical area, such as a WI-FI network, or an IEEE 802.11 style network.

According to another aspect of the invention, large-scale networks are also

20   handled. For large-scale networks, a hierarchical approach is applied whereby the set of links is partitioned into clusters. The links in each cluster are scheduled somewhat independently from the links in other clusters, and intercluster interference is modeled as static ambient noise. Interaction between clusters is modeled with a fixed-point equation, which determines the level of inter-cluster

25   interference. At a higher level, scheduling can be done at the cluster level, rather than at the link level.

For embodiments that minimize total power, we find our optimal power control policies are such that each node is either transmitting at peak power to a single receiver or not transmitting at all, which makes it simpler to implement

30   from the standpoint of computational resources and speed. This also means that

nodes can go to sleep much of the time, when they are not transmitting or
receiving, potentially conserving a great deal of energy. The optimal link
schedule time-shares a small number of optimal subsets of links (~ L + 1 for a
network with L links) in order to achieve the required data rates. The collection

5   of optimal transmission modes depends on the level of ambient noise and the
capacity allocations on links.

A byproduct of solving the scheduling and power control problem yields
link sensitivities that provide the change in the minimal total average power with
respect to a perturbation of the required data rate on a link. The minimal required

10   average power is a convex function of the required data rates on each link. This
leads us to a routing algorithm.

Testing of the invention revealed that that using minimum-energy paths to
route traffic and TDMA (time division multiple access) to schedule links is near-
optimal in low noise regimes and in the case where the required average data

15   rates are small. As the level of ambient noise increases, or the required average
data rates increase, our optimal routing policy exploits the use of multiple paths
to support higher data rates, and the optimal scheduling policy makes use of
concurrent transmissions on links. We find that non-minimum energy paths can
be exploited to increase throughput, despite the fact that all links share a common

20   bandwidth.

Preferred embodiments of the invention will now be described. Example
implementations and simulations are provided, but do not limit the invention in
its broader aspects and are not necessary for understanding or implementing the
methods of the invention as fully and separately described. Methods of the

25   invention may be implemented in any node of a network, or in a dedicated
centralized control node.

Suppose there are N stationary nodes, labeled by the integers 1,2, ..., N. A
set ε of $L_\varepsilon = |\varepsilon|$ transmission links, among the possible $N (N - 1)$ links between
nodes, constitutes a network topology.

For simplicity of exposition, we divide time into slots, each of equal duration and indexed by the positive integers. Transmissions begin and end on slot boundaries. For a given link $l = (i,j)$, the transmitter node i uses a signal power $P_m(l)$ in slot m. The path gain from node i to node j is given by $G(i,j)$, and can model the effects of signal attenuation due to distance, channel fading and shadowing, as well as antenna gain patterns. We model path gains $G(i,j)$ as being constant over the time frame being scheduled. As mentioned, the invention is most effective with relatively constant channel conditions. If the channel conditions are rapidly changing, the path may still be assumed constant, but the time period of scheduling might be kept smaller, e.g., scheduling over 100 time slots instead of over 200 in response to changing channel conditions.

The transmitting and receiving nodes of link l are denoted by $T(l)$ and $R(l)$ respectively. The received signal power at node $R(l)$ in slot m from the transmitter $T(l)$ is thus given by $P_m(l)G(T(l), R(l))$. However, signals emanating from other transmitters appear to the receiver $R(l)$ as interference, and there is ambient thermal noise to contend with as well. The signal to interference and noise ratio (SIR) for link l in slot m is defined as

$$\gamma_m(l) = \frac{G(T(l), R(l))P_m(l)}{\sum_{k:k\neq l} P_m(k)G(T(k), R(l)) + n_{R(l)}} \qquad (1)$$

where n_j is the "ambient noise" power at the receiver at node j. For now we assume that the ambient noise power at each node does not change from slot to slot, but we will relax this assumption later in a hierarchical approach that represents a preferred embodiment.

The data rate of the single wireless channel embodied by link l during slot m can be modeled as a function of the SIR, $\gamma_m (l)$. It is assumed that the achieved

data rate on link l during slot m, $X_m(l)$, is a linear function of the SIR, γ_m (l), and the total available bandwidth W. For simplicity of explanation, all links are assumed to share the same frequency band of width W. Using the Gaussian approximation to compute the bit-error-rate (BER), the data rate of a link l with a

5   tolerable BER of 10^{-q} and using BPSK modulation is given by

$$X_m(l) = W'\gamma_m(l) \quad \text{where} \quad W' = \frac{W}{2q \log_2 10}.$$
(2)

10

Let $\vec{P}_m = (P_m(1), P_m(2), ... P_m(L_\varepsilon))$ be the network power vector for slot m.

Let $P^{max}(i)$ be the maximum transmission power for node i. Let $\varepsilon(i)$ be the links

15   in ε that originate at node i.

Each node must conform to the peak transmission power constraint in every slot:

$$0 \le \sum_{l \in \varepsilon(i)} P_m(l) \le P^{max}(i) \text{ and}$$
$$0 \le P_m(l), \text{for all } m \ge 1.$$
(3)

Using (2) and (1), the achieved data rate for link l in slot m is

20

$$X_m = W'(\frac{G(T(l), R(l))P_m(l)}{\sum_{k : k \neq l} G(T(k), R(l))P_m(k) + n_{R(l)}}).$$

The long-term average rate of link l is then defined as

$$X^{avg}(l) = \lim_{m \to \infty} \frac{1}{m} \sum_{k=1}^{m} X_k(l).$$

25   For each link l, let $C(l)$ be a given minimum acceptable average data rate, i.e., we must have

(4) $\qquad$ $X^{avg}(l) \geq C(l)$, for all $l \in \varepsilon$.

Define the required minimum average rate vector as

$\bar{C} = (C(1), C(2), ..., C(L_\varepsilon))$.

The average power consumed by the transmitter for link l, $P^{avg}(l)$, is

$$P^{avg}(l) = \lim_{m \to \infty} \frac{1}{m} \sum_{k=1}^{m} P_k(l).$$

Define the average network power vector as

$\bar{P}^{avg} = P^{avg}(1), P^{avg}(2), ..., P^{avg}(L_\varepsilon))$.

There may or may not exist a sequence of network power vectors $\bar{P}_1, \bar{P}_2, ...$

that satisfy (3) and (4). If there does exist a sequence of such network power

vectors, our aim is to minimize the total average power given by $h(\bar{P}^{avg})$, where

(5) $\qquad$ $h(\bar{P}^{avg}) = \sum_{l \in \varepsilon} P^{avg}(l)$.

A systematic approach is used by the invention to compute a

schedule of network power vectors $\bar{P}_1, \bar{P}_2, ...$, satisfying the peak power

constraints (3) and the minimum average rate constraints (4), such that $h(\bar{P}^{avg})$ is

minimized. This primal problem is succinctly stated as

(6) $\qquad$ $\min \left\{ h(\bar{P}^{avg}) \right\}$ subject to (3) and (4).

Note this optimization involves choosing optimal power levels in

each slot for each transmitter. Using a duality approach the problem is reduced to

a convex optimization problem over a *single* slot. The duality approach is

preferred to solve the stated minimization in view of constraints. More generally,

however, a linear program may be used to reach a solution, as will be appreciated

by artisans.

<u>Duality Approach</u>

Let $\bar{n} = (n_{R(1)}, n_{R(2)}, ..., n_{R(L_\varepsilon)})$ be ambient noise power vector. Let the value *of*

the

optimal cost in the problem (6) as a function of $\vec{C}$ and $\bar{n}$ be denoted by $H(\vec{C}, \bar{n})$. If for a given value of $\vec{C}$ and $\bar{n}$, no schedule of network power vectors exists satisfying (3) and (4), define $H(\vec{C}, \bar{n}) = +\infty$. It can easily be seen that for a fixed value of $\vec{C}$, $H(\vec{C}, \bar{n})$ is monotone increasing in $\bar{n}$. Also, it can be shown that

5   for a fixed value of $\bar{n}$, $H(\vec{C}, \bar{n})$ is a convex function of $\vec{C}$.

Define a set of dual variables $\vec{\beta} = \{\beta(1), \beta 2, ..., \beta(L_\ell)\}$ for each link. Define a "potential" function V according to

$$V(\vec{P}, \vec{C}, \vec{X}) = h(\vec{P}) + \sum_{l \in \ell} \beta(l)[C(l) - X(l)].$$

10   The dual objective function is defined as

$$g(\vec{\beta}) = \min\left\{V(\vec{P}^{avg}, \vec{C}, \vec{X}^{avg})\right\} \text{ subject to (3)}.$$

Note the absence of the minimum rate constraints (4) in the definition of $g(\vec{\beta})$. A primary advantage of the restatement is that the number of variables to

15   be optimized is smaller. A secondary advantage is that the optimal values of the dual variables yield link rate sensitivities, used in embodiments of the invention for routing. For any non-negative vector $\vec{\beta}$, using (4), note that

$$H(\vec{C}, \bar{n}) \geq \min\left\{V(\vec{P}^{avg}, \vec{C}, \vec{X}^{avg})\right\}, \text{ subject to (3) and (4)}$$

$$\geq \min\left\{V(\vec{P}^{avg}, \vec{C}, \vec{X}^{avg})\right\}, \text{ subject to (3)} \qquad (7)$$

$$= g(\vec{\beta}).$$

20   Thus, for any non-negative vector $\vec{\beta}$, the minimum value of the objective function in the optimization problem (6) is lower bounded by $g(\vec{\beta})$. This observation leads to the dual optimization problem,

$$(8) \qquad \max\{g(\vec{\beta}) : \vec{\beta} \geq \vec{0}\}.$$

A convexity argument can be used to show that in fact we have

$$H(\vec{C},\vec{n}) \;=\; \max\left\{g(\vec{\beta}):\vec{\beta}\geq\vec{0}\right\}$$

(9)

$$=\; g(\vec{\beta}^{*}).$$

Computation of $g(\vec{\beta})$ involves optimizing over all schedules of network power vectors satisfying the peak power constraint in every slot.

5   However, since the potential function $V(\vec{P},\vec{C},\vec{X})$ is linear in $\vec{P},\vec{C}$, and $\vec{X}$, it follows that $g(\vec{\beta})$ can be computed by an optimization over a single slot, i.e.

$$g(\vec{\beta}) = \min\left\{V(\vec{P},\vec{C},\vec{X}):\vec{P}\in S_P\right\},$$

where $\vec{X}=\vec{X}(\vec{P})$ is defined as in (2) and (1), and S_P is defined as the polyhedral set

10      $S_P = \left\{\vec{P}:\Sigma_{l\in\varepsilon(i)}P(l)\leq P^{\max}(i) \text{ for all } i \text{ and } 0\leq P(l) \text{ for all } l\in\varepsilon\right\}$. Let M be the number of extreme points of S_P, and let $\vec{P}_m^{ext}, m=1,2,\ldots M$ denote the extreme points of S_P. By definition, each point in S_P can be represented as a convex combination of $\vec{P}_m^{ext}, m=1,2,\ldots M$. An upper bound on M is $2^{L\varepsilon}$. If M_i is the number of links emanating from node i, then $M = \prod_{i=1}^{N}(1+M_i)$.

15   A convexity argument then shows that

$$g(\vec{\beta}) = \min\left\{V(\vec{P}_m^{ext},\vec{C},\vec{X}(\vec{P}_m^{ext})):1\leq m\leq M\right\}.$$

Thus, the complexity of computing $g(\vec{\beta})$ is $O(M)$. In fact, note that $V(\vec{P}_m^{ext},\vec{C},\vec{X}(\vec{P}_m^{ext}))$ is an affine function of $\vec{\beta}$, which implies that the dual objective function $g(\vec{\beta})$ is the *pointwise minimum* of M affine functions, i.e.

$$g(\vec{\beta}) = \min_{1\leq m\leq M}\left\{a'_m\vec{\beta}+b_m\right\}.$$

(10)

20   An iterative ascent algorithm may be used to solve the dual optimization problem of equation (8). Exploiting the piecewise linearity of $g(\vec{\beta})$, the iterative ascent algorithm converges in a finite number of iterations. Alternately, by introducing a slack variable, the dual optimization problem of equation (8) can be

reduced to a linear program and be efficiently solved using interior point methods.

We'll now discuss a termination condition of the iterative ascent algorithm. For a given $\bar{n}$, if the required minimum rate vector $\bar{C}$ is infeasible, i.e. $H(\bar{C},\bar{n}) = +\infty$, it can be seen that $g(\vec{\beta})$ is unbounded from above over the set of all $\vec{\beta} \geq 0$. Otherwise, it is easy to see that

$$H(\bar{C},\bar{n}) \leq \sum_{i=1}^{N} P^{\max}(i).$$

Thus we can safely declare $\bar{C}$ and $\bar{n}$ infeasible if we find a value of $\vec{\beta}$ such that

$$g(\vec{\beta}) > \sum_{i=1}^{N} P^{\max}(i).$$

Computing an Optimal Link Scheduling Policy

Solving the dual problem (8) yields the optimal dual variable vector and extremal network power vectors $P^{*,i}$, such that

$$\begin{aligned} g(\vec{\beta}^*) &= \min\{g(\vec{\beta}) : \vec{\beta} \geq 0\} \\ &= V(\vec{P}^{*,i}, \vec{C}, \vec{X}(\vec{P}^{*,i})) . \end{aligned}$$

(11)

The vectors $P^{*,i}$ are extreme points of S_P that represent optimal transmission modes and the power levels of the transmitters in those transmission modes. In other words, assuming $H(\bar{C},\bar{n})$ is finite, an optimal schedule of network power vectors exists that consists solely of these extremal network power vectors $P^{*,i}$. This means that in the optimal policies we find, in each slot, every node is either not transmitting at all, or is transmitting at the maximum possible peak power to exactly one receiver. Moreover, since a hyperplane in $(L_\epsilon + 1)$ dimensional Euclidean space is determined by $L_\epsilon + 1$ linearly independent

points contained within it, an optimal policy can be constructed that consists of at most $L_\epsilon + 1$ extremal network power vectors $P^{*,i}$. Let K be the number of extremal network power vectors $P^{*,i}$ such that (11) holds. Define $\hat{K} = \min\{K, L_\epsilon + 1\}$. We thus have

$$H(\vec{C}, \vec{n}) = g(\vec{\beta}^*) = V(\vec{P}^{*,i}, \vec{C}, \vec{X}(\vec{P}^{*,i})),$$

5

for all i such that $1 \le i \le \hat{K}$.

In any optimal policy (assuming $H(\vec{C}, \bar{n})$ is finite), the average rate on each link l, $X^{avg}(l)$, is exactly equal to $C(1)$. Otherwise, we could decrease the total average power further without violating any rate constraints, thus

10   contradicting the optimality of the solution. Let $X^{*,i}(l)$ denote the rate of link l corresponding the optimal extremal network power vector $P^{*,i}$. Assuming $H(\vec{C}, \bar{n})$ is finite, it can be shown that (9) guarantees the existence of a "weight vector" $\vec{\lambda}^* = \{\lambda^*(1), \lambda^*(2), \lambda^*(\hat{K})\}$ such that the equations (12) and (13) below are satisfied:

15   (12)

$$\sum_{i=1}^{\hat{K}} \lambda^*(i) X^{*,i}(l) = C(l) \quad \text{for all links } l \in \mathcal{E}$$

$$\sum_{i=1}^{\hat{K}} \lambda^*(i) = 1 \quad \text{where } \lambda^*(i) \ge 0.$$

                                                                      (13)

Note that $\hat{K} \le L_\epsilon + 1$, so the above system of equations is always overdetermined. There must be $\hat{K} + 1$ of these equations which are linearly independent. Once we

20   have identified such a set of equations, we solve them by inverting a $(\hat{K} + 1) \times (\hat{K} + 1)$ matrix.

The value of $\lambda^*(i)$ indicates the relative frequency at which the extremal network power vector $P^{*,i}$ is utilized in an optimal policy. This then determines a family of optimal policies, which can be constructed by alternating between the

extremal network power vectors in accordance with the weight vector $\vec{\lambda}^*$. A specific optimal policy, for example, can be constructed using a pseudo-random number generator to select which extremal network power vector is used in each slot, such that the network power vector $P^{*,i}$ is used with probability $\lambda^*(i)$.

Reducing Complexity

The algorithm developed to solve the dual problem considers all M transmission modes. However, in the optimal schedule we have no more than $L_e + 1$ transmission modes. Since M can be as large as 2^{L_e}, the complexity of minimizing the dual objective function can be exponential. Thus, reducing the set of possible transmission modes considered can greatly reduce complexity. A natural consequence of the invention for a network of nodes with omni-directional antennas is that no node transmits or receives data at the same time in the optimal schedule due to high self interference. This observation can reduce the number of candidate transmission modes significantly. In general, in many cases it is possible using heuristics to eliminate many obviously inefficient transmission nodes from consideration, since they are unlikely to be used in an optimal policy.

To summarize the preferred scheduling embodiment just discussed and make some general observations about it, artisans will appreciate that the general steps included are to measure the channel parameters between transmitter and receivers in order to assess the corresponding data rates on each link for each possible transmission mode. Using a primal optimization approach, duty cycles of each transmission modes in an optimal scheduling policy can be calculated by formulation of the problem as a linear program. Alternatively, using a dual optimatization approach, we can first identify a relatively small set of transmission modes that comprise an optimal scheduling policy. The identification of this small set of transmission modes can also be posed as a linear program. Once such a set of transmission modes is identified, a set of linear

equations can be solved to identify the duty cycles of each transmission mode in the set. Once an optimal scheduling policy is calculated, it can be disseminated to all transmitters and receivers so that the optimal transmission modes can be realized in a synchronous manner.

5

Hierarchical Scheduling

For scheduling a network with a large number of links, increased speed may be realized by taking a hierarchical approach while applying the general scheduling discussed above. This can avoid a large amount of computation when

10 the number of links renders the scheduling calculation too expensive. The basic idea is to schedule links hierarchically.. In the hierarchical approach, we partition the set of edges ε into J disjoint subsets of edges ε(1), ε(2),... ε(J), called clusters. We thus have $\varepsilon = U_{j=1}^{J}\varepsilon(j)$. Since the links in the same cluster must coordinate to implement the scheduling algorithm discussed above, it is

15 convenient to group links into clusters such that the links belonging to the same cluster are in geographic proximity to each other.

Let $\overline{C}(j)$ be the minimum rate vector for cluster j, i.e. the components of $\overline{C}(j)$ consist of the components of $\overline{C}$ which are the minimum rates for each of the links belonging to cluster j. Similarly, let $\overline{n}(j)$ be the ambient noise vector for

20 cluster j, i.e. the components of $\overline{n}(j)$ consist of the components of $\overline{n}$ which are the ambient noise powers for each of the receivers belonging to cluster j.

Decoupling the Scheduling for Each Cluster

When we partition the links in the entire network into clusters, we assume

25 that the number of links in any given cluster is limited so that if the network consisted of only the links in the cluster, it is computationally feasible to use the method described above to schedule the links in the cluster. Let $H_j(\overline{C}(j),\overline{n}(j))$ be the minimal total average transmit power required for meeting the average data rate requirements for only those links belonging to cluster j. In other words,

the links in all other clusters besides cluster j are assumed to be absent or idle in the definition of $H_j(\overline{C}(j), \overline{n}(j))$. The value of $H_j(\overline{C}(j), \overline{n}(j))$, as well as a corresponding schedule for the links in cluster j, can be found by application of the embodiments described above.

Of course, the noise at a given receiver will not only consist of interference from other links in the *same cluster* and ambient thermal noise, but interference from links in *different* clusters will also be present. The power of the interference from other clusters will vary from slot to slot, in accordance with the link schedules used in each of the clusters. However, suppose we model the additional noise from interference in other clusters as static ambient noise.

Specifically, suppose that $\overline{N}(j) = (N_j(1), N_j(2), ..., N_j(L_{\varepsilon(j)}))$ consists of the total "average ambient noise" for the receivers of links in cluster j. In order to calculate the value of $\overline{N}(j)$, first define $\overline{P}^{avg}(k) = (P_k^{avg}(1), P_k^{avg}(2), ... P_k^{avg}(L_{\varepsilon(k)}))$ as the average transmission power vector for the transmitters of the links in cluster k. The value of $\overline{P}^{avg}(k)$ is obtained as a byproduct of computing $H_k(\overline{C}(k), \overline{n}(k))$ and the associated schedule for cluster k. Indeed we have

$$H_k(\overline{C}(k), \overline{n}(k)) = \sum_{l' \in L_{c(k)}} P_k^{avg}(l').$$

Consider link l' in cluster k. The transmitter of link l' transmits with average power $P_k^{avg}(l')$. Thus the *average* power of the interference caused by link l' in cluster k to the receiver of link l in cluster j is $G(T(l'), R(l)) P_k^{avg}(l')$. The value of $N_j(l)$ is obtained by summing the total contribution from all such links l' in all other clusters other than j, and adding the thermal ambient noise at receiver $n_{R(l)}$, i.e. we have

$$N_j(l) = n_{R(l)} + \sum_{k:k \neq j} \sum_{l' \in L_{c(k)}} G(T(l'), R(l)) P_k^{avg}(l').$$

(14)

Let $\overline{N}$ be the concatenation of the noise vectors $\overline{N}(1), \overline{N}(2),..., \overline{N}(J)$. From the discussion above, the vector $\overline{N}$ is determined by the global rate requirement vector $\overline{C}$ and the global ambient thermal noise vector $\overline{n}$. We can denote this mapping by a function $F(.,.)$, i.e.

5   (15) $\overline{N} = F(\overline{C}, \overline{n})$.

Coordinating the Clusters: Finding a Fixed Point

In general we will have $\overline{N} \geq \overline{n}$, so we need to take into account the effect of inter-cluster interference in the scheduling of each individual cluster. The actual ambient noise vector we seek is $\overline{N}^*$, where $\overline{N}^*$ satisfies the fixed point

10   equation

            (16) $\overline{N}^* = F(\overline{C}, \overline{N}^*)$.

This equation may be solved iteratively. In particular, let $\overline{N}^k$ be the estimate of the solution at the kth iteration. We can start with a noise vector that consists only of ambient *thermal* noise, i.e. $\overline{N}^0 = \overline{n}$. We then find a sequence of

15   estimates using the recursion $\overline{N}^{k+1} = F(\overline{C}, \overline{N}^k)$. We have performed a series of numerical experiments, and have found in every case that such an iterative algorithm finds a fixed point.

If each component of $F(\overline{C}, \overline{N})$ is a monotone function of $\overline{N}$, it is easy to establish that the iterations above will also converge to the smallest solution of

20   equation (16), assuming a solution exists. In the case where each cluster is sufficiently distant from all other clusters, all transmissions emanating from a given cluster can be modeled as a point source. In this case $F(\overline{C}, \overline{N})$ is a monotone function of $H_j(\overline{C}(j), \overline{N}(j))$ for all j, which in turn are monotone functions of $\overline{N}$. Hence, the convergence of the iterative algorithm can be proved

25   when all clusters are sufficiently distant from each other. We also believe, but cannot prove, that $F(\overline{C}, \overline{N})$ is a monotone function of $\overline{N}$ in all cases.

To summarize, we propose that each cluster first calculates a schedule, assuming all other links in other clusters are idle and there is no inter-cluster interference. After this calculation, we can compute the incident *average* interference at each receiver from links that belong to other clusters. Taking into account this average inter-cluster interference, we again calculate a schedule for each cluster. Proceeding inductively, we recalculate the incident average interference for each receiver from the transmitters belonging to other clusters. We then again calculate a schedule for each cluster using the new value of incident average inter-cluster interference, and so on.

Accounting for Non-constant Inter-cluster Interference

After a fixed point solution $\overrightarrow{N}^*$ to (16) is found, we have a transmission schedule for each cluster in which we have assumed that the power of inter-cluster interference is *constant*. The constant is the average inter-cluster interference obtained from the solution to the fixed point equation (16).

However, since the emitted power from a cluster varies from slot to slot, this assumption is not true. Fortunately, essentially due to the convexity of the function $(a+bx)^{-1}$ with respect to x, the actual average SIR for any given link will be at least as large as the average SIR obtained by assuming that the power of inter-cluster interference is constant. Thus, the actual achieved data rate for each link is at least as large as it would be assuming constant power for inter-cluster interference. In practice, each cluster could communicate its schedule to nearby clusters, and the data rate used in each slot can be appropriately adjusted to account for the non-constant inter-cluster interference.

To prove this, suppose link l belongs to cluster j and let $X^{avg}(l)$ be the actual average data rate achieved for link l, taking into account that the power of the inter-interference varies from slot to slot. Also, let $\hat{X}^{avg}(l)$ be the average data rate achieved link l assuming that there is constant power ambient noise $N_j^*(l)$. We wish to show that $X^{avg}(l) \geq \hat{X}^{avg}(l)$.

Recall that $N_j^*(l)$ is determined from the solution to the fixed point equation (16). In particular, if $n_{R(l)}(m)$ is the total average ambient noise incident at the receiver $R(l)$ in slot m, then

$$N_j^*(l) = \lim_{n \to \infty} \frac{1}{n} \sum_{m=1}^{n} n_{R(l)}(m) \,.$$

(17)

5   Suppose the fraction of time in which the transmission mode i is used in the schedule for cluster j is $\lambda^*(i)$, where transmission mode i is given by $P_j^{*,i} = (P_j^{*,i}(1), P_m^{*,i}(2), ..., P_j^{*,i}(L_{\varepsilon(j)}))$. Let $S_n(i)$ be the set of slots with index less than or equal to n where transmission mode i is used in cluster j. In fact we assume a stronger condition than in (17), namely

10

$$N_j^*(l) = \lim_{n \to \infty} \frac{1}{|S_n(i)|} \sum_{m \in S_n(i)} n_{R(l)}(m) \,,$$

(18)

15   for each transmission mode i in the schedule for cluster j. This will be true, for example, if the pseudorandom number generators for selecting transmission modes in each of the different clusters are independent. Moving on to the proof, we have

20

$$
\begin{aligned}
X^{avg}(l) &= \lim_{n \to \infty} \frac{1}{n} \sum_{m=1}^{n} X_m(l) \\
&= \lim_{n \to \infty} \frac{1}{n} \sum_{m=1}^{n} W'\left(\frac{G(T(l), R(l))P_m(l)}{\sum_{k:k \neq l} G(T(k), R(l))P_m(k) + n_{R(l)}(m)}\right) \\
&= \sum_i \lambda^*(i) \lim_{n \to \infty} \frac{1}{|S_n(i)|} \sum_{m \in S_n(i)} W'\left(\frac{G(T(l), R(l))P_j^{*,i}(l)}{\sum_{k:k \neq l} G(T(k), R(l))P_j^{*,i}(k) + n_{R(l)}(m)}\right) \\
&\geq \sum_i \lambda^*(i) W'\left(\frac{G(T(l), R(l))P_j^{*,i}(l)}{\sum_{k:k \neq l} G(T(k), R(l))P_j^{*,i}(k) + N_j^*(l)}\right) \\
&= \sum_i \lambda^*(i) X^{*,i}(l) = \hat{X}^{avg}(l) \geq C(l) \,,
\end{aligned}
$$

where the first inequality follows from (18) and the convexity of the function $(a+bx)^{-1}$ with respect to x.

Scheduling at the Cluster Level

Above, we have assumed that the links in each cluster can be active in each slot, i.e., all of the clusters are active in each slot. In certain situations, this may result in very high levels of inter-cluster interference, particularly when the links in different clusters are in close proximity.

As an alternative, we can group the clusters into different edge sets. A given edge set consists of the union of some subset of all the clusters, and each cluster belongs to exactly one edge set. The set of all slots is partitioned in such a way that each slot is reserved for links that belong to a given edge set.

With a suitable grouping of clusters into edge sets, we can insure that the clusters belonging to a given edge set are sufficiently separated in space. This will then limit the inter-cluster interference for clusters belonging to the same edge set. Each edge set can then be scheduled using the method discussed in the previous subsections.

More generally, we could formulate the cluster scheduling problem in a similar way to the link scheduling problem considered a above on an entire network basis. However, it appears that satisfactory schedules can be found by only considering a small collection of edge sets, where each edge set is assigned the same fraction of the overall system bandwidth. Moreover, by limiting the number of edge sets to a small constant, the scalability of the overall approach is significantly enhanced, both in terms of computation complexity, and the ease to which the overall algorithm can be implemented in a distributed way. We also note that, alternatively, the edge sets can be multiplexed in frequency rather than in time, as artisans will recognize.

Routing and Capacity Allocation

As described above, scheduling conducted according to the invention can
find an optimal link scheduling and power control policy to support a given
traffic rate on each link in the network while consuming minimum power.
Additionally, with a change in the statement of the constraints, scheduling of the
5   invention may be used to find optimal link and power control policies to
maximize data capacity. We also have developed a method to construct a policy
which allocates traffic rates on each link in accordance with a routing algorithm,
given a traffic matrix which describes the rate at which traffic is to be carried
between specific source-destination pairs. The routing algorithm is guided by the
10   computation of the minimum cost associated with optimal scheduling and power
control for supporting traffic rates on each link that have already been allocated,
as described in the previous section.

For example, consider a series of iterations, where at a given iteration we
wish to support a small amount of additional traffic from one of the given source-
15   destination pairs. Initially, no traffic is supported, i.e. the required minimum data
rate on each link is zero. We compute the optimal values for the dual variables,

$g(\vec{\beta})$ Using $g(\vec{\beta}) = \min\left\{V(\vec{P},\vec{C},\vec{X}) : \vec{P} \in S_P\right\}$, we can estimate the cost of

supporting additional traffic on each link using a first order Taylor series
approximation. For example, suppose we wish to evaluate a given route r. Let $\vec{r}$
20   be the L_ε dimensional vector, such that the component $r(l) = 1$ if link l is

included in the route $\vec{r}$, and $r(l) = 0$ otherwise. If we route an additional $\in$ units
of traffic along route r, the required data rate vector will increase from

$\overline{C}$ to $\overline{C} + \in \vec{r}$. The cost of supporting the additional $\in$ units of traffic along route r
can be determined from the approximation

25

$$H(\vec{C} = \in \vec{r}) = H(\vec{C}) + \in \sum_{l \in \varepsilon} \beta^*(l)r(l).$$

Therefore, in order to determine the best possible path along which an
additional increment of traffic should be routed, we can use a shortest path

algorithm (such as Dijkstra's algorithm or the Bellman-Ford algorithm), where
we set the weight for link l to the sensitivity value $\beta^*(l)$. After we have
identified the shortest path, we attempt to support the additional traffic along this
path. If the new value of $\overline{C}$ is infeasible, we either reduce the step-size ϵ until

5   the additional traffic can be supported, try supporting additional traffic for
another source-destination pair, or otherwise reach a prespecified termination
condition.

Indeed, since $H(\bullet)$ is convex, we can use the optimal routing framework
developed by Bertsekas et al. (e.g., see, D. Bertsekas and J. Tsitsiklis, "Parallel

10   and Distributed Computation: Numerical Methods", Prentice Hall 1989.). In this
class of algorithms, any feasible routing is first chosen. By incrementally
adjusting the routing in an iterative manner, flows are shifted towards shortest
paths at each iteration, and eventually a globally optimum routing is obtained.
There are many possible variations, for example regarding whether flow is

15   shifted simultaneously for every source destination pair, or whether flow is
shifted one at a time for each source destination pair. In the present context, we
are faced with a more difficult problem, since $H(\bullet)$ is not differentiable
everywhere. In addition, since evaluating the function $H(\bullet)$ is not trivial, it is
more difficult to ascertain whether a given routing is feasible, i.e. the capacity of

20   a given link depends on the rate carried by other links. Nevertheless, our initial
numerical experiments and the framework developed by Bertsekas et. al. suggest
that such an approach may be quite useful in practice.

The potential energy efficiency of a given link can be evaluated, assuming
that all other links are idle. For our model, the minimum transmission energy

25   required per bit on a link (i,j) is inversely proportional to $G(i,j)$. A minimum
energy path is defined as a path which has the smallest possible energy required
to transport a fixed amount of data, irrespective of the delay associated with
transporting that data. Previous work on routing in wireless networks (for
example see, S. Singh, M. Woo and C. S. Raghavendra, "Power-aware routing in

mobile ad hoc networks", Proc. of Fourth Annual ACMREEE Conference on
Mobile Computing and Networking pp. 181-190, Oct. 1998) is focused on energy
efficiency without regard to delay, i.e., such work proposes using minimum
energy paths.

5   We find that the paths over which traffic is allocated in some optimum
routings does not always correspond to using minimum energy paths. Our
simulations revealed, however, that when required data rates are sufficiently low,
our routing framework will apparently always use minimum energy paths

10   Experimental Simulation Examples

To illustrate the invention, we will now discuss some simulation examples
in the next section.

Hierarchical Scheduling (Example 1)

We consider a large fully connected wireless network consisting of 80
15   nodes and 150 links as shown in FIG. 1, distributed over a 200m x 200m field.
The network was divided into 16 clusters labeled by integers 1, 2,...16, and each
cluster consists of 5 or 6 nodes and 8 or 9 links. A link belongs to a cluster if the
transmitting node is within or on the boundary of that cluster. Moreover, each
link in the network belongs to exactly one cluster. The minimum average rate on
20   all links in the network is set to the same value. The peak power of all links is
identically set to 1 Watt and $W' = 10^6$. We applied our hierarchical approach over
the entire network by dividing it into edge sets in 3 different ways denoted by
cluster schedules X, Y and Z. Cluster schedule X schedules a single edge set
containing all 16 clusters. Cluster schedule Y schedules two edge sets each
25   consisting of clusters in a checker board pattern. i.e., {1,3,6,8,9,11,14,16} and
{2,4,5,7,10,12,13,15}. Each edge set in Y is scheduled for half the time. Cluster
schedule Z schedules four edge sets containing clusters {1,3,9,11}, {2,4,10,12},
{5,7,13,15} and {6,8,14,16} for a fourth of the time each. We plot the total
average transmit power consumed by all the links in the network as a function of
30   the (minimum) network throughput for each cluster schedule in FIGs. 2 and 3

corresponding to different values of thermal noise $n = 0.05$m W and $n = 0.2$ mW respectively. The thermal noise at all receivers is the set to be the same.

We find that for very low data rates (between 0 to 41 Mbps in fig. 3) it is energy efficient to enable all the 16 clusters simultaneously, regardless of the value of thermal noise. As the data rate along links increases (between 41 to 78 Mbps in FIG. 3), cluster schedule Y is the most energy efficient of the three configurations considered. For data rates beyond 78 Mbps (in FIG. 3), the energy efficient strategy is to enable the cluster schedule Z. For both values of thermal noise, Z is capable of supporting higher throughput than that achievable by X and Y.

For low rates, the optimal strategy in each cluster is a simple TDMA of links with long idle times. Therefore, the intercluster interference is small even when clusters are next to one another, making cluster schedule X the most energy efficient. However as the data rate requirement on links increases, links in each cluster are active for longer durations resulting in higher intercluster interference. In this case, schedules Y or Z are more energy efficient. We observed similar results to that in FIG. 6 for randomly generated network topologies as well.

Observe that by selecting a schedule based on the rate requirement we can realize an energy versus rate graph which is the minimum of the curves corresponding to the cluster schedules X, Y and Y in FIG. 6. In fact, by suitable timesharing of the cluster schedules we can achieve any rate in FIG.6 which lies in the convex hull of the minimum of the three cluster schedule curves.

Our iterative approach converges quickly to the fixed point solution for all cluster schedules considered making it practical for implementation in large wireless networks. We also observed that as the distance between the clusters in an edge set increases, the difference between the actual data rate and that obtained by assuming constant inter- cluster interference (over a slot) decreases. This is attributed to the weaker dependence of the transmission strategy of each cluster to the intercluster interference. For cluster schedule Z, we found that the

actual data rate was within 8% of the value obtained using constant inter cluster interference when the thermal noise $n = 0.2$ mW.

Example 2 String Topology

5

A string topology consists of a row of nodes connected by means of directed links as shown in FIG. 4. This topology is useful as a transport network to carry data through short hops but over potentially long total distances through relay nodes. Node 1 is the source of data and node 5 is the sink. Each node in this example has an omnidirectional antenna, and all nodes have identical peak transmission power constraints of 1 Watt. The path-loss between nodes is modeled as an inverse square of the distance, i.e., $G(i, j) = \dfrac{1}{d(i, j)^2}$. The ambient noise power at all the nodes is assumed to be constant. We compare the maximum throughput of the single session between node 1 to node 5 achieved by our link scheduling policy to a TDMA scheduling policy. The TDMA policy schedules exactly one link at a time, activating each link at maximum power for a fourth of the time. We plot the ratio of throughputs achieved by the our link scheduling algorithm to TDMA with increasing values of ambient noise in FIG. 5. The ambient noise is normalized with respect to the peak received power (from a single transmitter) in the network and is scaled by $\log_2(.)$ (for this and the remaining examples). The maximum throughput achieved by our policy is higher than TDMA for all values of ambient noise. In low noise regimes, TDMA is a near-optimal policy. However, as the level of ambient noise at nodes increases, the gains in throughput of our policy increase significantly. The optimal policy schedules multiple transmissions at the same time, even in fairly low ambient noise regimes, thereby exploiting spatial reuse and thus outperforming TDMA. This effect is more pronounced in moderate and high ambient noise regimes where the optimal policy schedules concurrent transmissions even though they are in close geographic proximity.

To get a sense of how energy efficient the optimal policy is as it supports increasing traffic demands, we plot the total average power with increasing traffic rates for the session between node 1 and node 5 in FIG. 6. For this experiment, we fix the level of the logarithm of the normalized value of ambient noise to -

5   0.67. This value corresponds to the 3rd data point on the x-axis in FIG. 5. We also set $W' = 10^7$.

FIG. 6 indicates that the total minimum average power is a linear function of the traffic demand for average rates below 4 Mbits/sec. Below 4 Mbits/sec, our scheduling method functioned essentially as TDMA. Specifically, only one link

10   is active at any time, each link is active for the same fraction and for some fraction of time all links are idle. As the traffic demand of the session increases beyond 4 Mbits/sec, the total average power increases at a faster rate. For traffic load between 4 Mbits/sec and 4.98 Mbits/sec, the transmission modes in the optimal policy are given by [{(1,2)}, {(2,3)}, {(3,4)} and {(1, 2), (4, 5)}]. For

15   traffic loads above 4.98 Mbits/sec to the maximum throughput possible, the optimal transmission modes are [{(1,2)}, {(2,3)}, {(3,4)}, {(1,2),(3,4)} and {(1,2),(4,5)}]. We see that in order to support high traffic loads, the optimal link scheduling policy activates a large number of links simultaneously. Note that the transmission modes in the optimal policy are half-duplex. Therefore,

20   transmissions in the optimal schedule cannot consume a total average power of more than 2000 mW for this topology.

Example 3 Diamond Topology

We also consider an asymmetric diamond topology as shown in FIG. 7 to

25   illustrate the substantial increase in throughput by splitting traffic over multiple routes including paths that are energy inefficient. Nodes in this topology are equipped with omnidirectional antennas, and the peak trans- mission power each node is fixed at 1 Watt. Node 1 is the only source of data and node 4 is the sink.

We assume $G(1,4) = \dfrac{1}{d(1,4)^4}$; the path loss between all other nodes is given by the

inverse square law of distance. We consider our integrated routing and scheduling algorithm over this diamond topology, where all possible routes from the source to the destination are allowed except for the single hop route (1,4). For comparison purposes, we also considered our scheduling algorithm where only

5   the links (1,2), and (2,4) are allowed to be used, which corresponds to routing over a single minimum energy path $1 \rightarrow 2 \rightarrow 4$.

We compare the ratio of throughputs for these polices in FIG. 8. Clearly, using multiple paths yields higher throughputs for all values of ambient noise. The increase in throughput by splitting traffic over multiple paths is significant

10   even for moderate levels of ambient noise. This result is somewhat surprising since all links are sharing a common bandwidth and we have a per-node peak power constraint. An intuitive explanation of this is that by splitting the traffic over both paths, the transmission modes {(1,2),(3,4)} and {(2,4),(1,3)}, which do not have much interference can be alternated in time. This results in substantial

15   delivery of data to the destination in every slot. If we only allow the path $1 \rightarrow 2$ $\rightarrow 4$, in order to avoid self interference, the links (1,2) and (2,4) must be active one at a time, so that node 4 will only be delivered data in every other slot.

To illustrate energy efficiency issues, we plot the total minimum average power with increasing traffic demand at node 1 in FIG. 9. The logarithm of the

20   normalized value of ambient noise for this point is 0.45 and corresponds to the *3rd* data point on the x-axis in FIG. 8. We set $W' = 10^7$. The maximum data rate achieved by TDMA using the minimum energy path $1 \rightarrow 2 \rightarrow 4$ is 3.65 Mbit/sec. In comparison, our policy is capable of supporting a data rate of up to 5.05 Mbits/sec by using both the minimum energy path as well as the non-minimum

25   energy path. For traffic loads below 3.65 Mbits/sec, our method produces a policy that functions as TDMA over the path $1 \rightarrow 2 \rightarrow 4$. As the traffic load increases beyond 3.65 Mbits/sec, the method results in an optimal policy that starts using both paths by scheduling transmission modes {(1, 2), (3,4)} and {(1,3), (2,4)} in addition to TDMA transmission modes. The average power

30   required to achieve higher traffic demands beyond 3.65 Mbits/sec increases with

a greater slope as can be seen in FIG. 9. The maximum throughput of 5.05 Mbits/sec is achieved by splitting traffic by using both paths and scheduling transmission modes {(1,2), (3,4)} and {(1,3), (2,4)} for a dominant fraction of time and scheduling transmission modes {(1,2)}, {(2,4)} for the remaining time.

5 The optimal policy transmits a fair amount of traffic on both available paths, but transmits a greater share of its traffic on its minimum energy path. We have noted a 10 to 20% reduction in the throughput gains of the optimal policy than what is shown in FIG. 8 for the case when $G(1,4) = \dfrac{1}{d(1,4)^2}$.

Example 4 Hierarchical Topology

10 A hierarchical topology as shown in FIG, 10 represents a complex topology such as an access network, where the number of nodes in each tier decrease as we get closer to the access point node 6. This experiment highlights the significant gains in throughput by jointly routing and scheduling to an alternative policy that optimally schedules links over pre-determined minimum

15 energy routes. Nodes 1, 2 and 3 are sources of data and node 6 is the sink. We assume $G(1,6) = \dfrac{1}{d(1,6)^4}$ and $G(2,6) = \dfrac{1}{d(2,6)^4}$; the path loss between all other nodes is given by the

inverse square law of distance. The minimum energy paths for the source nodes are: {1 → 3 → 6}, {2 → 3 → 6} and {3 → 6} respectively. Our integrated

20 routing and scheduling algorithm is allowed to utilize all possible paths to route their data to node 6. We constrain the rates of each source to be identical. We plot the ratio of the total maximum throughput of our routing policy to that achieved by using only the minimum energy paths, as a function of ambient noise in FIG. 11.

25 We find that at low noise levels, our policy supports a throughput at least 30% more than the data rate achieved using minimum energy paths alone. As the level of ambient noise increases, our policy supports a significantly higher throughput. The base policy schedules links in a TDMA sequence for all values

of ambient noise. The optimal policy schedules concurrent links even for low levels of ambient noise. In the optimal policy, nodes 1 and 2 route their traffic over non- minimum energy paths $1 \rightarrow 4 \rightarrow 6$ and $2 \rightarrow 5 \rightarrow 6$ respectively, apart from the minimum energy paths, for all values of ambient noise. For low ambient

5   noise, the optimal policy schedules the transmission modes {(1,3)}, {(2,3)} and {(3, 6)} according to TDMA but also allows modes {(1,4),(5,6)} and {(2,5),(4,6)} to be active for reasonable fractions of time. As the level of ambient noise increases, the optimal policy splits node 3's traffic over paths $3 \rightarrow 4 \rightarrow 6$ and $3 \rightarrow 5 \rightarrow 6$. In fact, for sufficiently high ambient noise, the optimal policy

10   schedules a large number of concurrent links, the dominant transmission modes being {(1,4), (5,6), (2,3)} and {(2,5),(4,6),(1,3)} and {(1,4), (2,5), (3,6)}.

Generalized Embodiments

        Methods of the invention as illustrated in the specific embodiments are a

15   teaching of more general embodiments of the invention, as artisans will appreciate. As one example, methods of the invention can minimize the total average transmitter and receiver energy required to achieve the target capacity on links in the network. The constraints and the value being minimized/maximized is simply changed. Another constraint we could impose is a maximum peak

20   power constraint for an arbitrary collection of nodes, rather than per each node. This may be useful to limit signal emissions from an entire network or subnetwork.

Minimizing Total Average Transmitter and Receiver Power

25   The total energy required to transmit a packet over a slot is the energy expended in the electronic circuitry to transmit at the desired power level. The efficiency of power amplifiers is typically around 10% and therefore, the total power consumption at node $T(l)$ link is roughly $10P(l)$. Energy involved in coding (e.g. convolution coding) packets may be treated as negligible.

The energy required to receive a packet of information is comprised of
two components. The first component is the electronic energy required to operate
PLL's, registers, etc. and this is proportional to the data rate of the link. The
second component is the energy required to decode the packet. While the

5   decoding energy increases greatly as the SINR of the link decreases, this
component of energy can be substantially lowered (by orders of magnitude) by
using Application Specific Integrated Circuits to decode the received signal.

We therefore ignore the decoding energy component and coarsely model
the power expended by a receiver $R(l)$ as a linear function of the data rate of link

10   l. Let $P_R(l)$ denote the power expended by node $R(l)$ to receive data at rate $X(l)$.
Then $P_R(l) = \theta(l)X(l)$ where $\theta(l)$ is the energy expended per bit that is constant for
each receiver node $R(l)$. The new cost function that we would like to minimize is

$$h(\overline{P}^{avg}) = \sum_{l \in \varepsilon} \alpha(l)P^{avg}(l) + \sum_{l \in \varepsilon} \theta(l)X^{avg}(l) \quad (19)$$

15   where $h(\overline{P}^{avg})$ is the sum total of average transmission and receiver power.
The dual objective function corresponding to the new primal function (19) would
have an additional average receiver power term. The dual problem corresponding
to the new primal problem is similar to (8) except that without loss of generality,
we can constrain $\beta(l) \geq \theta(l)$ for each link $l \in \varepsilon$. This constraint, $\beta(l) \geq \theta(l)$, allows

20   us to exploit the concavity property and use the link scheduling and power
control algorithms originally developed to solve problem (8), for the new dual
problem.

Accounting for receiver power in our method changes the choice of routes
and the rate allocations on links in each route. The changes in the routing policy

25   are more pronounced in a network where nodes are in fair proximity to each
other. Using multiple hops in such topologies would consume higher receiver
energy than using a single hop, making multi-hop routing inefficient. In such
topologies, ignoring receiver energy consumption in the problem formulation
would have yielded multi-hop routing as the optimal routing policy.

As described above, embodiments of the invention provide an integrated routing, scheduling and power control framework that is well suited for slow fading wireless channels which are relatively constant for long durations of time. Outdoor wireless channels with strong line-of-sight paths typically tend to have a

5   very stable channel strength and could be approximated as a constant for a time interval (block fading model) ranging from a few to several minutes. By periodically measuring the channel and accounting for the changing traffic requirements for each source-destination pair, the invention can compute the optimal routing, scheduling and power control method and adapt it to the

10   changing network conditions.

While specific embodiments of the present invention have been shown and described, it should be understood that other modifications, substitutions and alternatives are apparent to one of ordinary skill in the art. Such modifications, substitutions and alternatives can be made without departing from the spirit and

15   scope of the invention, which should be determined from the appended claims.

Various features of the invention are set forth in the appended claims.

CLAIMS:

1.   A method for scheduling communication in a wireless
communications network, the network having a plurality of nodes, the method
comprising steps of:

        measuring channel parameters between arbitrary nodes in the
wireless communications network;

        for each possible transmission mode, identifying a signal to
interference plus noise ratio based upon the measured channel parameters;

        mapping the signal to interference plus noise ratio into a data rate
for the transmission modes; and

        from a subset of transmission modes that result from the step of
mapping, determining which of all of the transmission modes are scheduled to
meet minimum data rate constraints between links and minimize total average
power.

2.   The method of claim 1, wherein said step of measuring
measures channel parameters between all nodes in the wireless communication
network.

3.   The method of claim 1, wherein said step of measuring
measures channel parameters between a subset of all of the nodes in the
communication network, including nodes having no communication link at the
time of measuring.

4.   The method of claim 1, wherein said step of determining
comprises:
applying a linear program constrained by the minimum data rates between links
and the transmitting power of nodes.

5. The method of claim 1, further comprising a step of choosing path flows for routing communications through the links scheduled by said step of determining, wherein said step of choosing paths comprises:

determining an initial set of path flows between sources and destinations, and calculating a data rate carried on each link of the network to define a set of data rates;

for the set data rates, minimizing total power and calculating a resulting link sensitivity of the total power to a change in the data rate on each link to define calculated link sensitivity parameters;

using the calculated link sensitivity parameters to produce adjusted path flows;

re-calculating the carried data rate on each link for adjusted path flows, and recalculating the link sensitivity parameters;

iteratively repeating, if necessary, said steps of adjusting and re-calculating until total power used is acceptably small.

6. The method of claim 1, wherein said step of determining determines the links that define a transmission mode, and the duty cycle for each transmitting node in the transmission mode.

7. The method of claim 6, wherein a transmission mode determined in said step of determining further comprises a transmission power and data rate for each of the links.

8. The method of claim 1, wherein said step of determining determines a vector whose dimensionality is equal to the number transmission modes in the subset, wherein the vector determines the duty cycle of the transmission modes that are scheduled

9.   The method of claim 8, wherein a minimum specified data rate on each link is a constraint on the vector that is incorporated in a linear program to minimize the total transmission power.

10.   The method of claim 1 wherein said step of determining comprises application of a convex duality calculation.

11.   The method of claim 10, wherein the convex duality calculation comprises:

defining a numerical value for each transmission mode in the subset of transmission modes, wherein the numerical value is the sum of powers for each link plus a difference term for each link, and wherein each difference term is equal to a difference between a required minimum data rate on the link and an associated data rate on the link for a given transmission mode, and wherein difference terms summed in the numerical value are weighted in proportion to corresponding dual variables defined for each link;

restating a modified optimization criteria defined as the smallest numerical value from said step of defining, over the set of transmission modes in the subset of transmission modes;

determining optimal values for the dual variables which maximize the modified optimization criteria;

determining a set of transmission modes whose associated numerical values achieve the minimum in the modified optimization criteria, wherein the dual variables are set to optimal values as determined in said step of determining optimal values.

12.   The method of claim 1, applied in a hierarchal manner and carried out on a cluster of links, further comprising the steps of dividing a set of links into clusters, and carrying out said steps of measuring and determining for each cluster.

13.   The method of claim 12, wherein inter-cluster interference is modeled as static ambient noise.

5   14.   The method of claim 13, wherein interaction between clusters is modeled with a fixed-point equation that determines the level of inter-cluster interference.

15.   The method of claim 1, carried out by a node in the network.

10   :

16.   A method for routing communications using a transmission mode scheduled according to claim 1, further comprising steps of:

specifying a traffic matrix wherein each element in the matrix comprises a rate of data traffic to be moved between a transmitting node and a

15   receiving node;

testing a candidate routing using the traffic matrix to induce a data rate on each link;

scheduling according to said steps of measuring, identifying, mapping and determining to determine transmission power and link sensitivity

20   parameters indicating sensitivity of total power to changes in data rate on each link;

iteratively searching for a routing to reduce average power.

17.   The method of claim 16, wherein the value of link sensitivity

25   parameters are determined by steps comprising:

defining a numerical value for each transmission mode in the subset of transmission modes, wherein the numerical value is the sum of powers for each link plus a difference term for each link, and wherein each difference term is equal to a difference between a required minimum data rate on the link

30   and an associated data rate on the link for a given transmission mode, and

wherein difference terms summed in the numerical value are weighted in proportion to a dual variable defined for each link;

restating a modified optimization criteria defined as the smallest numerical value from said step of defining over the set of transmission modes in

5   the subset of transmission modes;

determining optimal values for the dual variables which maximize the modified optimization criteria;

determining a set of transmission modes whose associated numerical values achieve the minimum in the modified optimization criteria,

10   wherein the dual variables are set to optimal values as determined in said step of determining a set of transmission modes.

such that the sensitivity value for each link is equal to the optimal value of respective dual variable determined by said step of determining optimal values for the dual variables.

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18.   A method for scheduling communication in a wireless communications network, the network having a plurality of nodes, the method comprising steps of:

measuring channel parameters between arbitrary nodes in the

20   wireless communications network;

for each possible transmission mode, identifying a signal to interference plus noise ratio based upon the measured channel parameters;

mapping the signal to interference plus noise ratio into a data rate for the transmission modes; and

25   from a subset of transmission modes that result from the step of mapping, determining which of all of the transmission modes may be scheduled to maximize total throughput while meeting a maximum power constraint on each link in the network.

19.   A method for scheduling communication in a wireless communications network, the network having a plurality of nodes, the method comprising steps of:

measuring channel parameters between arbitrary nodes in the

5   wireless communications network;

determining a set of transmission modes, each transmission mode in specifying a state of operation for links of the network, said step of determining being conducted by minimizing a weighted sum of expended transmission powers across the links of said network in view of the channel

10   parameters measured in said step of measuring, such that each link in the network achieves a predetermined minimum data rate

20.   A method for routing information through a wireless communication network, the network having a plurality of nodes and a plurality

15   of potential links between the nodes, the method comprising steps of:

determining a traffic matrix that specifies the rate of information transport between each pair of nodes in the network;

setting an initial routing of traffic on said links of the network in order to support the traffic matrix determined in said step of determining a traffic

20   matrix;

determining required data rates on the links of the wireless communication network for the initial routing of traffic set in said step of setting;

computing a sensitivity of links in response to change of data rate;

iteratively adjusting the routing of traffic using the sensitivity of

25   links so that the weighted sum of expended transmission powers across the links of the network is reduced and repeating said steps of determining and computing.

21.   The method of claim 20, wherein said step of computing computes a sensitivity parameter for all links in the network.

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22. The method of claim 21, wherein the value of link sensitivity parameters are determined by steps comprising:

defining a numerical value for each transmission mode in the subset of transmission modes, wherein the numerical value is the sum of powers for each link plus a difference term for each link, and wherein each difference term is equal to a difference between a required minimum data rate on the link and an associated data rate on the link for a given transmission mode, and wherein difference terms summed in the numerical value are weighted in proportion to a dual variable defined for each link;

restating a modified optimization criteria defined as the smallest numerical value from said step of defining over the set of transmission modes in the subset of transmission modes;

determining optimal values for the dual variables which maximize the modified optimization criteria;

determining a set of transmission modes whose associated numerical values achieve the minimum in the modified optimization criteria, wherein the dual variables are set to optimal values as determined in said step of determining optimal values;

such that the sensitivity value for each link is equal to the optimal value of a respective dual variable determined by said step of determining optimal values for the dual variables.

23. The method of claim 20, wherein said step of computing computes sensitivity for a subset of links in the network.

24. The method of claim 20, wherein said step of iteratively adjusting and repeating is repeated until the weighted sum of expended transmission powers does not significantly change in response to adjusting the routing.

25. A method for scheduling transmission of information through a wireless communication network, the network having a plurality of nodes and a plurality of potential links between the nodes, the method comprising steps of

5   measuring channel parameters between arbitrary nodes in the wireless communications network;

determining a set of transmission modes for the wireless communication network while accounting for the channel parameters measured in said step of measuring, wherein each transmission mode in the said set

10   specifies a state of operation for the communication links of said network, with the objective of maximizing a weighted sum of data rates across the links of said network, and such that the power consumed by each transmitter is no greater than a predetermined maximum value.

15   26. A method for scheduling transmission of information through a wireless communication network, the network having a plurality of nodes and a plurality of potential links between the nodes, the method comprising steps of

measuring channel parameters between arbitrary nodes in the wireless communications network;

20   determining a set of transmission modes for the wireless communication network while accounting for the channel parameters measured in said step of measuring, wherein each transmission mode in the said set specifies a state of operation for the communication links of said network, with the objective of minimizing a numerical value determined by power expended on

25   links of the wireless communication network, such that prespecified data rates on links of said network can be achieved by use the set of transmission modes.

27. The method of claim 26, wherein said step of determining includes determining a duty cycle for each transmission mode in the set of transmission modes determined in said step of determining.

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INTERNATIONAL SEARCH REPORT

International application No.

PCT/US03/28076

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7)   : H04B 1/38; H04M 1/00

US CL   :   455/63.1, 67.11, 69, 67.13, 453, 452.2, 522; 370/252

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

    U.S. : 455/63.1, 67.11, 69, 67.13, 453, 452.2, 522; 370/252

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2002/0051425 A1 (LARSSON) 02 May 2002, see entire document	1-4, 6, 7, 10, 15 and 18-21
Y,P	US 2002/0193133 A1 (SHIBUTANI) 19 December 2002, see entire document	1-4, 6, 7, 10, 15 and 18-21
X,E --- A,E	US 2003/0202491 A1 (TIEDEMANN, JR. et al) 30 October 2003, see paragraphs 0021-0026, 0046 and 0058.	1-4, 6, 7, 10, 15 and 18-21 ---------- 5, 8, 9, 11-14, 16 and 17
X,E --- A,E	US 2003/0204615 A1 (WEI et al) 30 October 2003, see paragraphs 0009, 0010, 0017-0037.	1 and 18-20 ---------- 2-4, 6, 7, 10, 15 and 21
Y,P	US 2003/0157900 A1 (GAAL et al) 21 August 2003, see entire document.	1 and 18-20

☐ Further documents are listed in the continuation of Box C.   ☐   See patent family annex.

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"E"	earlier application or patent published on or after the international filing date		
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed	"&"	document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
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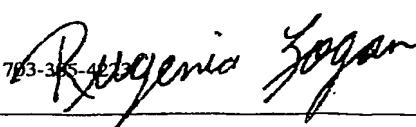
Form PCT/ISA/210 (second sheet) (July 1998)